NUMERICAL ANALYSIS ON THE BEHAVIOUR OF CFRP SHEAR-STRENGTHENED RC DEEP BEAMS WITH LARGE SQUARE AND CIRCULAR OPENINGS

SHIM CHEE WEI

Report submitted in partial fulfilment of the requirements
for the award of the degree of
Bachelor Eng. (Hons.) Civil Engineering

Faculty of Civil Engineering and Earth Resources
UNIVERSITI MALAYSIA PAHANG

JUNE 2015

ABSTRACT

This study presents a finite element analysis to investigate the behaviour of reinforced concrete deep beams with square and circular openings. Deep beams are always constructed at the lower floors as transfer beams to transfer the loads from the entire building to the foundations. Reinforced concrete (RC) acts as one of the most essential building materials and it is widely used in the construction due to its low pricing, efficiency and strength of the reinforced concretes as well as its stiffness. Openings are inevitable for the architectural and mechanical purpose to accommodate the conduits. However, presence of openings in the deep beams will significantly reduce the load capacity of the deep beams, as well as excessive cracking and deflection. Strengthening by Carbon Fibre Reinforced Polymer helps in regain the load bearing capacity of the deep beams. Researches were focus on the experimental work and hence this study conducted in terms of the numerical aspects and finite element analysis. ANSYS CivilFEM 12.0, a finite element modelling and analysis software, was used to analysis the deep beams. Three – dimensional modelling of RC deep beams was adopted in this study. A total of 14 beams including one control beam were modelled as simply supported beam with openings where the locations of the openings were at the support which was 300 mm from the edge of the beams. Two incremental loads were applied at the 800 mm from the edge of the beams. The beams was symmetrical in shape. The beams had the cross sections of 120 mm x 600 mm and 2400 mm in length with square and circular openings. The objectives of this study were to determine the most effective strengthening method by using CFRP in terms of load-deflection behaviours, crack patterns, stress and strain contours. This study was validated by experimental results. Various strengthening methods were used to identify the most effective method of strengthening which included orientation of CFRP in vertical alignment (90º), horizontal alignment (0º), whole piece, cut strips, surface strengthening and U-wrap strengthening. Deep beams with openings failed due to shear cracks because of the sharp edges of the openings. From the finding, the square opening and circular opening experienced a reduction of 62.0% and 51.3% in beam capacity, respectively. From the various strengthening configurations of CFRP, configuration with vertical alignment, whole piece and U-wrap strengthening method was the most effective method. CFRP restored the load bearing capacity with most effective method by 63.0% and 85.0% for deep beams with square and circular openings respectively. A comparison between the numerical and experiments results showed that a comparable agreement on the load deflection behaviours and strong agreement on the crack patterns.

ABSTRAK

Kajian ini membentangkan satu analisis unsur terhingga untuk mengkaji sifat/kelakuan rasuk konkrit bertetulang dalam dengan pembukaan segi empat tepat dan bulat. Rasuk konkrit bertetulang dalam sentiasa dibina di tingkat yang lebih rendah untuk memindahkan beban daripada seluruh bangunan kepada asas-asas. Konkrit Bertetulang (RC) sebagai salah satu bahan binaan yang paling penting dan ia digunakan secara meluas dalam pembinaan disebabkan oleh harga yang rendah, kecekapan dan kekuatan konkrit bertetulang serta kekejangan yang tinggi. Bukaan adalah tidak dapat dielakkan bagi tujuan senibina dan mekanikal untuk menampung konduit. Walaubagaimanapun, kewujudan bukaan pada gelombang-gelombang yang mendalam dengan ketara akan mengurangkan kapasiti beban gelombang-gelombang yang mendalam, serta berlebihan keretakan dan pesongan. Pengukuhan dengan polimer diperkukuh gentian karbon membantu dalam pemulihan kekuatan dalam kapasiti konkrit bertetulang. Walau bagaimanapun, penyelidikan sebelum adalah lebih fokus kepada kerja-kerja eksperimen dan oleh yang demikian kajian ini dijalankan dari segi aspek berangka dan analisis unsur terhingga. ANSYS CivilFEM 12.0, satu unsur terhingga pemodelan dan analisis perisian, telah digunakan untuk analisis gelombang-gelombang yang mendalam. Tiga – pemodelan dimensi rasuk mendalam RC telah digunakan dalam kajian ini. Sejumlah 14 rasuk yang termasuk satu rasuk kawalan adalah peringkat sebagai rasuk semata-mata disokong dengan bukaan di mana lokasi yang bukaan berada pada penyokong yang seluas 300 mm dari tepi gelombang-gelombangnya. Dua beban kenaikan akan dikenakan pada dalam 800 mm dari tepi gelombang-gelombangnya. Rasuk dalam adalah simetri dalam bentuk. Rasuk dalam yang mempunyai bahagian cross 120 mm x 600 mm dan 2400 mm panjang dengan pembukaan segi empat tepat dan bulatan. Objektif kajian ini adalah untuk menentukan kaedah pengukuhan yang berkesan dengan menggunakan CFRP dari segi beban-pesongan tingkah laku, corak retak, kontur tekanan dan ketegangan. Kajian ini telah disahkan oleh keputusan eksperimen. Pelbagai kaedah pengukuhan telah digunakan untuk mengenal pasti kaedah yang paling berkesan bagi pengukuhan yang merangkumi orientasi CFRP di jajaran menegak (90º), penjajaran mendatar (0º), seluruh bahagian, memotong jalur, permukaan pengukuhan dan pemantapan U-Balut. Rasuk yang mendalam dengan bukaan gagal kerana retak ricih kerana tepi tajam bukaan. Daripada kajian, pembukaan segi empat tepat dan bulatan mengalami penurunan sebanyak 62.0% dan 51.3% dalam rasuk kapasiti masing-masing. Dari pelbagai konfigurasi pengukuhan daripada CFRP, konfigurasi dengan jajaran menegak, seluruh bahagian dan kaedah pengukuhan U-Balut adalah kaedah yang paling berkesan. CFRP semula keupayaan galas dengan kaedah paling berkesan 85.0% dan 63.0% bagi rasuk dalam yang mendalam dengan pembukaan Pekeliling dan bukaan persegi masing-masing. Perbandingan antara yang berangka dan keputusan ujikaji menunjukkan bahawa keputusan setanding beban pesongan sifat rasuk dan keputusan yang kukuh pada pola retak.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

D	Depth
E	Modulus of elasticity
f_c'	Maximum concrete strength
f_t	Tensile strength
Ø	Diameter
ε	Strain
L	Span
s	Displacement
τ	Bond stress
τ_{max}	Maximum bond stress
<	Less than
>	Greater than

LIST OF ABBREVIATION

2D	2 – dimensional
3D	3 – dimensional
CB	Control beam
CFRP	Carbon Fibre Reinforced Polymer
DBC	RC Deep beams with circular openings
DBCS	RC deep beams with circular openings strengthened by CFRP
DBS	RC deep beams with square openings
DBSS	RC deep beams with square openings strengthened by CFRP
FE	Finite element
FEA	Finite element analysis
FEM	Finite element modelling
FRP	Fibre Reinforced Polymer
kN	Kilo-Newton
m	metre
mm	Millimetre
RC	Reinforced concrete

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Rapid development in some developing nations has encouraged the construction of high-rise buildings and sky scrapers. Due to the heavy load from the enormous buildings, deep beams are always constructed at the lower floors as transfer beams to transfer the load from the entire building to the foundations. Reinforced concrete (RC) as one of the most essential building materials and it is widely used in the construction due to its low pricing, efficiency and strength of the reinforced concrete as well as its stiffness (Dadvar, 2014). Thus, RC deep beams are playing an important role in tall buildings, offshore structures, and foundations (Kong, 2006). Sometimes, the creation of openings on the reinforced concrete (RC) deep beams is needed to accommodate the utility services conduits such as electrical wiring and piping (Hawileh et. al., 2012a).

Some of the researches and studies have been done on the RC deep beams with openings recently. Dadvar (2014) tested the behaviour of reinforced concrete beams and high walls with finite element analysis. Campione and Minafò (2012) experimentally and analytically evaluated the influence of circular openings in reinfroced concrete deep beams with low shear span-to-depth ratio. Hemanth (2012) studied the behaviour of FRP strengthed deep beams with openings through experiments and numerical study by using ANSYS. Five deep beams with openings without shear reinforcements were tested under three-point loading. Another finite element analysis on simply supported RC beams with circular openings had been conducted by Hafiz et. al. in 2014. Alsaeq (2014) investigated the usage of Carbon Fibre Reinforced Polymer (CFRP) to increase the structural strength of RC deep beams with openings.

1.1.1 Reinforced Concrete Deep Beams

RC deep beam which means the depth of the beam is comparable to the span length of the RC beam itself. However, the Eurocode 2 (1984) (draft): *Common Unified Rules for Concrete Structures* does not directly provide guidelines for the design of the deep beams. Instead, it is required to refer to clauses 18.18 of the CEB-FIP Model Code (1978). Moreover, the design is not covered in BS 8110 as well, this can be known from the statement that "*for the design of deep beams, reference should be made to specialist literature*". This is similar to the Draft Eurocode 2 which explicitly states that "*it does not apply however to deep beams…*" and refer to CEB-FIP Model Code. The main design documents, recently, available are the American code ACI 318-83 (revised 1986), CIRIA Guide 2, the CEB-FIP Model Code and the Canadian code CAN-A23.3-M84 (Kong, 2006). However, American Concrete Institute (ACI) states that, in the ACI 318-08 code, specification of deep beam should have either clear spans equal to or less than four times of the overall member depth or regions with concentrated loads within twice the member depth from the face of the support.

1.1.2 Reinforced Concrete Deep Beams with Openings

In recent decade, techniques used on the openings in deep beams are improving and much advanced. Openings are needed nowadays to allow the installation of conduits for utility pipelines such as electricity, air conditioning, gas pipeline, fire-rescues system, and computer networks. Opening in deep beam sometimes is not constructed together during casting of the RC deep beam but it is necessary to be made from core boring method on the RC deep beam on the existing building. The load path will be changed and shear capacity of the RC deep beam will be reduced if the openings intercept the stress field of the loading and the reaction point (Campione & Minafò, 2012). Several of shapes and sizes of openings could be found on the openings of RC deep beams, generally, the openings in the area where shear is dominant which is near to the support (Hafiz et. al., 2014). Openings are inevitable now due to its convenience for the utility pipelines and most important it can reduce the overall story heights of buildings by creating openings on the RC deep beams.

1.1.3 Finite Element Analysis by ANSYS Civil FEM 12.0

ANSYS CivilFEM 12.0, a structural modelling and analysis software, is used for finite element analysis by numerical method and modelling of RC deep beams with openings is done in 3-Dimensional. ANSYS CivilFEM 12.0 is a high-end solutions for advanced civil engineering projects. ANSYS CivilFEM 12.0 can be used for creating engineering solutions spanning static, dynamics, linear and non-linear problems. This civil structural software is capable for structural elements and the checking code included Eurocode, Russian SP, ACI, Brazilian Code, ASTM, British Code, AISC and Chinese Code (https://caeai.com/ansys-software-support/civilfem-ansys-software). Moreno et. al. quoted that "CivilFEM is at the present time one of the most advanced tools that engineers can embrace, a project that is committed with a time and with a permanent vocation of investigation and development." (Moreno et. al., 2001).

Finite element analysis is a numerical method to solve some complicated problems. Numerical solutions can now been obtained through finite element analysis for even very complicated stress problems (Roylance, 2001). Finite element analysis can be applied in many areas of studies, e.g. structure analysis, solid mechanics, dynamics, thermal analysis, electrical analysis, biomaterials and etc. Finite element analysis is originally developed for solving solid mechanics problem. At first, input such as boundary conditions will be set into ANSYS CivilFEM 12.0 and the software will provide output, for examples, stress, strain, displacements, load-deflection diagram and deformation of the models.

1.1.4 Carbon Fibre Reinforced Polymer (CFRP)

Carbon Fibre Reinforced Polymer (CFRP), also *Carbon Fibre Reinforced Plastic*, and it is similar to fibre glass. *Fibre-reinforced polymer* (FRP) is a composited polymer matrix reinforced with fibre while CFRP is polymer matrix composite material reinforcing by carbon fibre. Carbon fibre is woven into a textile material and resin such as epoxy resin is applied and allowed to cure. The polymer used in the material usually will be epoxy, vinylester or polyester thermosetting plastic and phenol formaldehyde resins (Masuelli, 2013). CFRP gains its popularity recently due to its best strength to weight ration among all the construction materials so it is very strong. CFRP can be considered as the improvement on glass fibre reinforced polymer although CFRP is much more expensive than glass fibre reinforced polymer. The advantages of light weight, resistance to corrosion and high strength of CFRP made this material to be an excellent option for use as external reinforcing for construction elements. Recently, CFRP material is showing a continuous great promise in using as strengthening material in reinforced concrete structures (Khalifa et. al., 1998). At the early stage, CFRP tends to be used in the sport car manufacturing production line. Strong and lightweight materials are needed for the car racing. CFRP is used in air craft production as well because CFRP is honoured with its minimum weight but great strength (http://www.technologystudent.com/joints/carfib1.html). CFRP is introduced to strengthen the beam so that the weakening done by the opening can be improved. CFRP material is distinguished by its extremely high strength and rigidity and differ so much from that of their matrix material. Unlike Glass Fibre Reinforced Polymers, CFRP exhibit considerably greater rigidity, sharply enhanced electrical and thermal conductivity and a lower density, due to its advantages in physical properties, which lead CFRP to the application in aerospace engineering when CFRP is introduced. CFRP is not being used in Civil Engineering field until 1991. This material was first applied in the Civil Engineering field in the strengthening of the Ibach Bridge near Luceme in Switzerland in 1991. CFRP, embedded in polyester resin, is reinforced and composed from very thin carbon fibres with diameter only 5 – 10 μm (Flaga, 2000).

1.1.5 Importance of Strengthening

Increasing in safety requirements, changing of social needs, more stringent design standards and the deterioration of existing reinforced concrete infrastructures are requesting the demands in strengthening of the structures (Godat et. al., 2007).

FRP repairs work by reducing the stress range experienced in the metal substrate, this method should be effective before and after crack initiation, as long as the bond between the FRP and the underlying metal is maintained (Alemdar et al., 2012). Safety of residents and users in a particular building can only be guaranteed if the damaged or vulnerable reinforced concrete structures have been repaired and strengthened. Beams, as the vital structural elements to withstand loads, laterally and vertically, so investigation on the efficient method to repair and strengthen the beams are necessary in terms of maintaining the safety of the structures, users and residents. In this study, several of strengthening methods will be tried out in the ANSYS modelling until the two most effective methods are determined.

As the infrastructures continue to age, there is an increase of need for effective maintenance, repair, rehabilitation, and retrofit. As the time passes by, many aging structural members is not providing the load capacity as compared to the original design. This situation is due to the cracking of concrete, corrosion of steel or insufficient deformation capacity to withstand the lateral and vertical load. These older structural members may not have sufficient strength, stiffness or load capacity for the applied load (Sezen, 2012). Inadequate of strength in these structures and components may risk the lives of users and residents and damage to property of public.

1.2 PROBLEM STATEMENT

The use of deep beams at lower levels for high rise buildings is more common nowadays due to the rapid development. Usage of deep beams with openings in the high rise buildings for both residential and commercial properties and purposes has increased significantly due to the convenience and economic considerations. Openings are convenience to be created for the utilities purpose and without increasing the stories overall height. However, creating openings in fulfilling the architectural or mechanical requirements to achieve the building’s function would result in the reduction of shear capacity of the particular elements, thus it leads to the questioning of safety of the building. Whenever the openings are inevitable, safety precautions step should be taken to ensure the recovery of strength capacity of the elements (Hemanth, 2012). The strength capacity reduced is not only to withstand the vertical and self-weight of the building but also needed to withstand the lateral load, wind load, and bending moment force. The reduction in the shear capacity is more significant when opening fully interrupts the natural load path (Hawileh et al., 2012a). Different shapes, percentages of reduction, and locations of the openings will have different degree of strength reduction in the RC deep beams.

Traditionally, externally bolting and steel plates are practiced in civil industry to strengthen the structural elements. Additional reinforcements are added externally to the surfaces of the structural members for additional capacity. The success of this technique is that attached as new reinforcement for the structural members and relieves heavily on the physical properties of long-term durability of the reinforcement materials (Shaw, n.d.). However, there are some disadvantages for the bolting and steel plates thus leading this technique to a less common practice in the industry. The main disadvantages of using bolting plates are the steel plates are not protected by concrete as the same ways of internal reinforcement, the durability and corrosion effects remain questioned, precaution steps should be taken before installing the steel plates, surface of the steel plates should be carefully prepared to resist the corrosion, weight of the steel plates make the transportation difficult and etc.

Due to the unsuitability of the bolting and steel plates system in the industry, modelling and finite element analysis on the CFRP should be carried out to investigate the shear capacity recovery on the RC deep beams with openings for further development in the civil industry. Finite element analysis can be used to predict the behaviour of the RC deep beams with openings through modelling and meshing.

1.3 OBJECTIVES OF STUDY

i. To determine the behaviour of deep beams with openings without strengthening and strengthening using CFRP in terms of load deflection behaviour, crack pattern, stress and strain contours.
ii. To identify the effect of openings with different shapes, i.e. circular and square, in deep beam.
iii. To identify the most effective strengthening method to strengthen the RC deep beam with opening by CFRP.

1.4 SCOPE OF STUDY

In this particular study, a commercial finite element analysis software, ANSYS CivilFEM 12.0, was adopted to run the numerical analysis of finite element method to solve the approximate solutions of stresses, strains and displacements at each node of elements. Numerical analysis was adopted to identify the behaviour of RC deep beams with openings as well as the behaviours of beams after strengthening using CFRP. Three fundamental type deep beams (control beam, deep beams with openings and deep beams with openings strengthened by CFRP) were considered in this investigation for each shapes. A deep beam without any opening acted as a control beam while the remaining modelled deep beams were with openings. One of the modelled deep beams with opening was not strengthened while the remaining deeps beams were modelled with different strengthening methods to identify the most effective strengthening method by applying CFRP around the openings. The simply – supported deep beams were tested by applying four point loading to evaluate the load deflection failure, crack pattern, stress and strain contours. The deep beams were tested to failure by constantly increased the force on the both point loads. The results from the modelling simulation were compared with the experimental result to determine the similarities and differences between the behaviours of deep beams.

The dimensions of the deep beam with opening that being studied are $120\,mm \times 600\,mm$ for the cross section of width and height and length of 2400 mm. The size of opening had been decided to be around 45% of reduction from the depth of the RC deep beam which is 270 mm in diameter for the circular opening while 270 mm for each side of the square opening. Meanwhile, the diameter of steel reinforcement for the RC deep beams with openings at tension region, which were bottom reinforcement, was 16 mm with a total of two reinforced steel bars. The diameter of steel reinforcement for the compression region, which was top region, is 10 mm with the number of two reinforcement steel bars. Four horizontal reinforcement bars with six millimetre were installed as well with 150mm from centre to centre each side. The shear link being used for this study was decided to be mild steel with six millimetres in diameter.